Reprinted from the Journal of The American Ceramic Society, Vol. 63, No. 5–6 May-June, 1980

Thermal Effects in Sharp-Particle Contact

B. R. LAWN,* B. J. HOCKEY,* and S. M. WIEDERHORN*

THE stress field produced in a surface contacted by a sharp indenting particle is elastic/plastic in nature,[1] which implies that part of the work of indentation must be dissipated about the contact zone as heat. At sufficiently high indentation rates, the heat generation occurs under adiabatic conditions. The corresponding increase in local temperature may contribute significantly, via thermal stress effects, to the net elastic/plastic field.[2] Since it is the inelastic component of the field which provides the primary driving force for any ensuing indentation cracks,[3] investigation of adiabatic heating is most pertinent to brittle ceramics.

In this study a model for accommodating adiabatic heating is developed in terms of indentation theory, with specific reference to contact data for soda-lime glass. Consider the fixed-profile indenter

Received December 20, 1979; revised copy received February 14, 1980.
Supported by the U.S. Office of Naval Research, Metallurgy and Ceramics Program.
At the time this work was done, the writers were with the Fracture and Deformation Division, National Bureau of Standards, Washington, D.C. 20234. B. R. Lawn was on study leave from the Department of Applied Physics, University of New South Wales, Kensington, New South Wales 2033, Australia.
*Member, the American Ceramic Society.

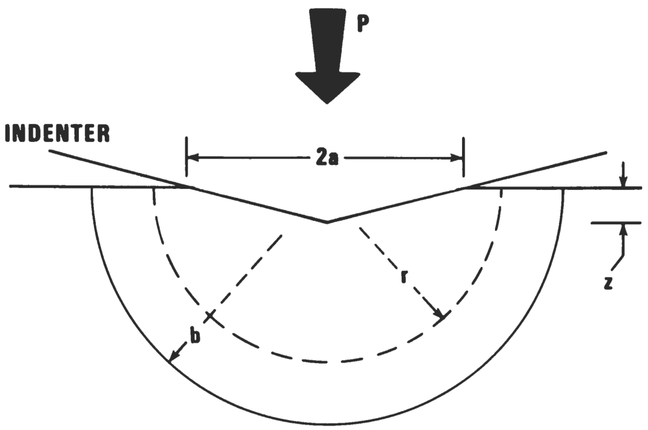

Fig. 1 Parameters of sharp-particle contact.

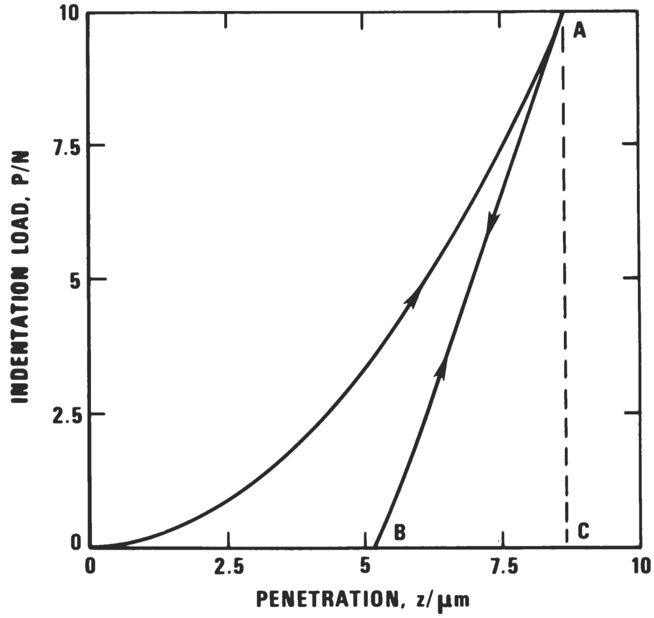

Fig. 2. Load/displacement response of Vickers indentation on soda-lime glass. Loading half-cycle 0*A* is elastic/plastic, unloading half-cycle *AB* (and subsequent reloading *BA*, etc.) is elastic. Areal ratio $f=0AB/0AC$ represents fraction of indentation energy dissipated within plastic zone. (Cycle carried out below indentation fracture threshold.)

at load P and penetration z in Fig. 1. Then for the loading half-cycle the field may be conveniently characterized in terms of geometrical similitude relations[1]: thus, both the penetration and the plastic zone (approximately hemispherical*) radius b scale spatially with the characteristic contact dimension a,

$$z/a=\cot\psi=\text{constant} \quad (1a)$$

$$b/a=\text{constant} \quad (1b)$$

where ψ is the indenter half-angle; again, the stress intensity scales with the mean contact pressure, which defines the hardness H for a given material,

$$P/\alpha_0 a^2=\text{constant}=H \quad (2)$$

where α_0 is a geometrical constant. For the unloading half-cycle the field may be regarded as essentially elastic (subsequent recycling up to peak load reproduces the unload response). Figure 2 shows a typical $P(z)$ response for Vickers indentation on soda-lime glass.

The preceding similarity relations may be used to evaluate the thermodynamics of the indentation cycle. The work done by the force $P(z)$ in effecting an incremental penetration δz is

$$\delta W=P(z)\delta z=[\alpha_0 H(a/b)^3 \cot\psi]b^2\delta b \quad (3)$$

where δb is the corresponding expansion in zone size. If a fraction f of this work is dissipated as heat and this dissipation occurs uniformly within the mass m_b behind the advancing elastic/plastic boundary, then an associated temperature increase may be found from

$$f\delta W=m_b c_p \delta T \quad (4)$$

with c_p the specific heat. Noting that $m_b=(2\pi b^3/3)\rho$, where ρ is the density, and that volume elements at any reference distance r from the contact origin will dissipate no energy until encompassed within b, δT may be integrated to give the net temperature increase over the zone radius. Thus, from Eqs. (3) and (4), for $0<r\leq b$,

$$\Delta T(r)=3\theta \int_r^{b^*} db/b=3\theta \ln (b^*/r) \quad (5)$$

where the asterisk denotes maximum penetration configuration and

$$\theta=(f\alpha_0 H/2\pi\rho c_p)(a/b)^3 \cot\psi \quad (6)$$

is a characteristic temperature for any given indenter/specimen system. It is readily shown that θ is the *average* temperature increase over the plastic zone (e.g. by integrating Eqs. (3) and (4) separately). A normalized plot of Eq. (5) in Fig. 3 indicates that the temperature increase near the point of contact can greatly exceed this average value.

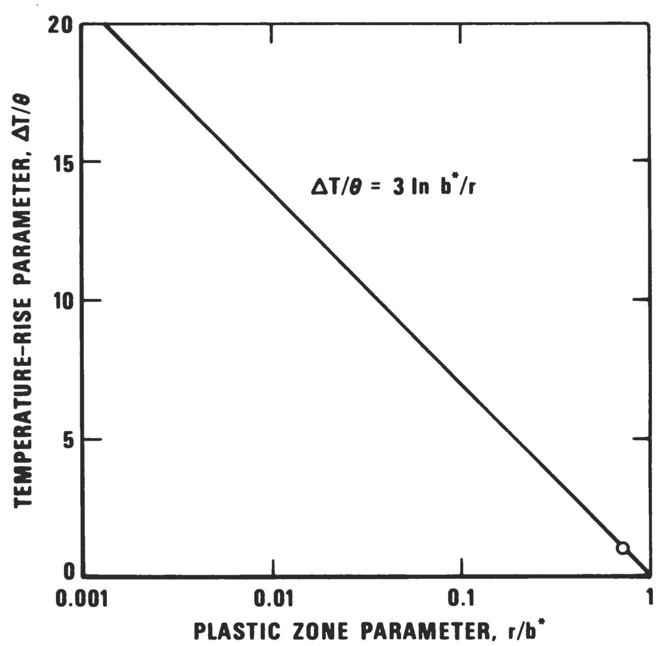

Fig. 3. Radial temperature distribution over plastic zone. Note that *average* temperature increase occurs at $r/b=0.72$ (circle).

As an illustrative example, consider Vickers indentations on soda-lime glass. Then, taking the impression half-diagonal as the characteristic dimension a, $\psi=74°$ (angle between pyramid edges) and $\alpha_0=2$; for glass, $H\approx5.5$ GPa, $\rho\approx2.5\times10^3$ kg m^{-3}, $c_p\approx600$ J

*This assumption is based on the work of Johnson (Ref. 1), who investigated the shape of the plastic zone in the vicinity of wedges and cones and found that material displacement is accommodated approximately by a radial expansion of the material surrounding the indentation.

$kg^{-1} K^{-1}$, $a \approx b$ (i.e. plastic zone confined to limits of impression[4]), and $f \approx 0.4$ (Fig. 2), giving $\theta \approx 133$ K. Thus the softening temperature, $\approx 690°C$, would be achieved within a surface region $r/b < 0.1$ (Fig. 3) in true adiabatic heating.

Although adiabatic conditions are unlikely to apply in any quasi-static Vickers test, they are almost certainly approached in solid-particle impact events, where the contact intervals are generally <1 μs. In Fig. 4, which shows impact sites on a glass surface, clear evidence exists for local molten "hot spots." The oblique incidence of the impacting particles used in obtaining the micrographs in this figure is particularly well suited, by means of its directional extruding effect, for providing information on the thermal processes involved. Particular note may be made of the fluidic "streamers" at the exit lip of the crater in Fig. 4(*B*), presumably trailed out from the extruded glass by the glancing particle. For soda-lime glass to behave in this fluid-like manner the relaxation time η/μ, where $\mu \approx 30$ GPa is the infinite-frequency shear modulus and η is the viscosity, must have been less than the contact time, ≈ 1 μs; i.e. the viscosity must have had a value $\eta \lesssim 30$ kPa s, which corresponds to $T \gtrsim 1100$ K (evaluated from published viscosity/temperature data[5]).

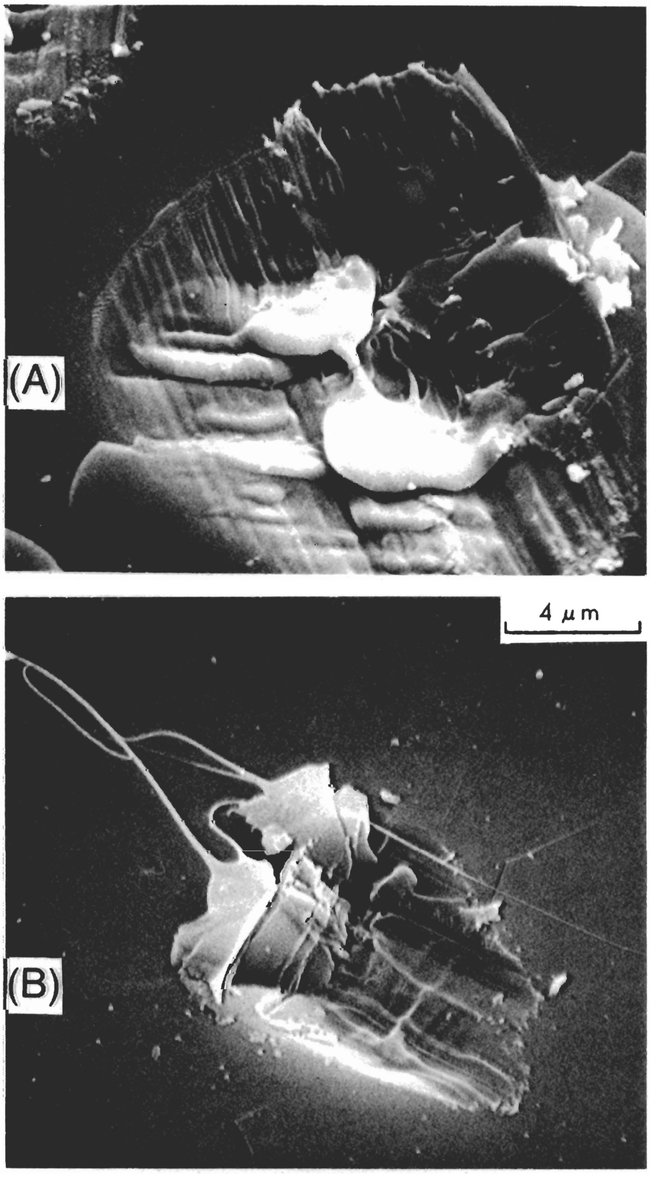

Fig. 4. Scanning electron micrographs of damage sites on soda-lime glass impacted with 150-mesh SiC particles. Particles incident at 15° to surface at (*A*) 94 ms^{-1} and (*B*) 54 ms^{-1}.

The model presented here should be recognized as highly idealized and therefore appropriate to first-approximation estimates only. For example, hardness is not strictly a material constant as implied in Eq. (2), but is some complex function of temperature, penetration rate, and indenter angle. Considerable uncertainty must accordingly arise from the use of quasi-static Vickers hardness in the analysis of impact patterns, particularly in those local regions of greatest temperature increase; indeed, the logarithmic singularity at the contact origin in Eq. (5) may be ascribed to misrepresentation of the essential flow properties in this vicinity. Nevertheless, the calculation may be usefully applied as a means of quantifying the potential extent of local melting in different ceramics, particularly on a relative basis. In this context it may be pointed out that analogous surface melting phenomena have been reported for impacts on alumina and mullite, materials with melting points $>>2000$ K.[6] Thermal effects might accordingly be expected to contribute to the material-removal processes involved in the erosion and wear of ceramics, particularly at contact loads below those at which chipping fracture modes begin to operate.[7]

Acknowledgments: The writers thank A. G. Evans for useful contributions and, especially, C. S. Yust, who first brought the melting phenomenon to their attention.

[1](*a*) D. Tabor, Hardness of Metals. Clarendon Press, Oxford, 1951
(*b*) K. L. Johnson, "The Correlation of Indentation Experiments," *J. Mech. Phys. Solids*, **18** [2] 115–26 (1970).
[2]A. G. Evans; pp. 1–14 in The Science of Ceramic Machining and Surface Finishing II, Edited by B. J. Hockey and R. W. Rice, *Natl. Bur. Stand.* (*U.S.*) *Spec. Publ.*, No. **562**, 1979.
[3]B. R. Lawn, A. G. Evans, and D. B. Marshall, "Elastic/Plastic Indentation Damage in Ceramics: I"; to be published in the *Journal of The American Ceramic Society*.
[4]J. T. Hagan and M. V. Swain, "The Origin of Median and Lateral Cracks Around Plastic Indents in Brittle Materials," *J. Phys. D*, **11** [15] 2091–2102 (1978).
[5]J. R. Hutchins III and R. V. Harrington; pp. 533–604 in Encyclopedia of Chemical Technology, Vol. 10, 2d ed. Edited by R. E. Kirk and D. F. Othmer Wiley-Interscience, New York, 1966.
[6]C. S. Yust and R. S. Crouse, "Melting at Particle Impact Sites During Erosion of Ceramics," *Wear*, **51** [1] 193–96 (1978).
[7]B. J Hockey and S. M. Wiederhorn; "Erosion of Ceramic Materials: The Role of Plastic Flow," in the Proceedings of the Fifth International Symposium on Erosion by Liquid and Solid Impact, held in Cambridge, England, Sept. 2–6, 1979.